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The pilot dimensions method: Reconciling Steering and Conformity in Workshops

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Abstract: In machining workshops, workpieces are produced according to dimensions known as *manufacturing dimensions*. For the same workpiece and the same manufacturing plan, several sets of manufacturing dimensions can be used but none satisfy simultaneously the two main missions workshops need to fulfil: (a) Ensuring conformity of products to their design dimension tolerances (also called blueprint tolerances) and (b) steering machines in order to compensate for tool wear.

The set of manufacturing dimensions obtained from the design dimensions using the minimal chain of dimensions method is optimal for a conformity check of workpieces but is practically unusable for steering machines because of the complexity of its relationships toward the tool correctors and tools dimensions.

The pilot dimensions method consists in, on the one hand, identifying and representing these tool correctors and these tool/program dimensions on the production drawings (besides the manufacturing dimensions) and, on other the other hand, determining their correction values through a mathematical set of relations after having measured the manufacturing dimensions on a workpiece. Doing so will strongly reduce adjustment time, reduce the number of workpieces used for adjustments and greatly enhance the quality of workpiece batches.

Keywords: Machining Processes, Production Control, Tolerance Charts, Tolerancing, Machining Steering

1 Steering of machines and conformity verification of products in workshops

Manufacturing workshops and, in particular, those who machine parts, have two essential missions:

- Guaranteeing conformity of the parts to the geometrical specifications indicated on their design drawing.
- Steering machines in order to obtain this conformity, through periodical adjustments of their tools.

Even when restricting the geometrical specifications to the one-direction dimensions case, such as, for instance, the dimensions positioning the surfaces of a revolute part (see figure 1), these two missions are difficult to conciliate in workshops today. It is one of the reasons why machining rejection rates are still very important, in spite of the high degree of accuracy of the used machines.

The conformity of a workpiece should be judged with respect to the dimensions indicated on the design drawing (see figure 1), that we are going to call the **design dimensions**, in this paper. They are often called blueprint dimensions in the english literature.

In order to steer machines, another dimensions system is required that we are going to call the **manufacturing dimensions** (figure 2 presents an example of set of manufacturing dimensions). This second system is different from the first one for several reasons: Firstly it can be impossible, at a given moment in the manufacturing process of a part, to measure a design dimension because, only one of the two surfaces, which the dimension connects, exists. It is however necessary to measure its position with respect to the others surfaces. Secondly design dimensions can be difficult to measure in workshops or difficult to use for the adjusting of the positions of the tools in the machine. This is why, in reality, the two systems of dimensions, design dimensions and manufacturing dimensions, coexist.

However, in workshops, it is not suitable to have to use two systems of dimensions, the first one to steer the machines, and the second one to check the conformity of workpieces. In reality, only one system of dimensions is used, in a more or less explicit way, simultaneously for the steering and for the conformity verification of workpieces. Unfortunately, as we are going to see it later on, none of the manufacturing dimensions sets can handle, alone, simultaneously both missions.

The aim of this paper is to present a method, called the **pilot dimensions method** (Goldschmidt 2009), which, by completing the optimal set of manufacturing dimensions for the verification, allows to use this same set of dimensions for the machine steering.

To illustrate our explanations, we are going to use the example of a part, presented in figure 1, machined on a lathe by a first tool (1), followed by a second shape tool (2). This drawing also carries the design dimensions of the part.

2 Choice of the manufacturing dimensions

2.1 Manufacturing dimensions for machine steering

From the steering point of view, the best solution is that the manufacturing dimensions locate directly the tools. Thus, any deviation on a manufacturing dimension can be corrected by modifying the position of the tool.

The determination of such a system of manufacturing dimensions is largely described in the literature (Johnson 1954, Mooney 1955, Gadzala 1959, Wade 1967, Wade 1983, Ngoi 1998), and a lot of work has been done to computerise this method (Irani 1989, Whybrew 1990, Britton 1996, Britton 1997, Ngoi 1995, Xue 2002, Ji 2006).

This method, often assigned to Wade (1967, 1983), consists in associating one manufacturing dimension to each tool. Each of these manufacturing dimensions connects one of the surfaces, machined by the tool (surfaces 2 and 3 on figure 2), to the reference surface of the part in contact with the machine chuck (surface 1).

The set of dimensions obtained can be rather different from the set of design dimensions. This is why the transfer of tolerances of the design dimensions to manufacturing dimensions, is done with a strong reduction in their values. For instance the dimension of 15 mm, which had a tolerance of 0.08 mm, now has a tolerance of 0.03 mm. This is the condition which guaranties, with the manufacturing dimension of 29 mm, the design dimension of 14 mm. In a general way, a large decrease in tolerance is the major disadvantage of this method of determining manufacturing dimensions.

Their use for the declaration of conformity can be very dangerous:

Because of their small intervals of tolerance, workpieces can easily be outside of these intervals and

be rejected. However the workpieces can be in conformity with the design dimensions tolerances.

The manufacturing dimension tolerances can even be so “tight” that it is impossible, even with a perfect tool adjustment, to respect them on all of the produced workpieces because of the random dispersion of their values due to the machine.

This method is ideal for the steering of production but is too constraining for the conformity verification of the products.

2.2 Manufacturing dimensions for conformity

A second approach, initiated in France by Bourdet (1973, 1975, 2007) (Fainguelelnt 1986), consists in preserving as many design dimensions as possible. A design dimension must be replaced by two manufacturing dimensions only if it connects surfaces which are not machined by the same workpiece carrier (In fact this condition is even too constraining. One can show that, under certain conditions, the design dimension can be preserved as a manufacturing dimension even if the surfaces which it connects are machines in two different workpiece carriers). The method used in this case is the minimal chain of dimensions method.

For the chosen example, all the surfaces are machined in the same workpiece carrier. Therefore, all the design dimensions become manufacturing dimensions without any loss of tolerance.

This method is optimal from a tolerance point of view but leads to manufacturing dimensions which can depend on several tool-parameters. For example the dimension of 14 mm depends on the correctors of position of tools (1) and (2), that we name, according to the surface numbers, C2 and C3 (see figure 3). But C2 also modifies the dimension of 15 and C3 that of 42. The adjustment of the process becomes much more complicated because it is necessary to take into account simultaneously deviations on several manufacturing dimensions to determine the correction value of the positions of the tools. This operation is very difficult to be done mentally by an operator in the unfavorable to reflection workshop environment.

This method is indeed optimal for the conformity verification of the products but is practically unusable for the steering.

Consequently, in companies, and in particular screw-machining ones, manufacturing dimensions are often selected in an empirical way and correspond either to “manufacturing dimensions for production steering” (Wade’s method) or to “manufacturing dimensions for conformity” (Bourdet’s method) or none of the dimensions sets obtained by these two academic methods.

It must be noted that a previous work of comparison of those two methods has had been done by Lehtihet and al (2000) but they take into account only the "simulated dimensions" of the Bourdet’s method. But those dimensions are used to verify the capability of the manufacturing plan to meet the design dimensions. The authors of the paper omits the manufacturing dimensions of this method used to measure workpieces.

3 Pilot dimensions

In order to preserve the most favorable set of manufacturing dimensions for the conformity inspection of products, we will retain the ones obtained by Bourdet’s method. Nevertheless, keeping in mind that these dimensions will be used for production steering, it is necessary to connect them to the tool correctors on the machine and provide operators with the adequate relationships.

The method that we propose consists, on the one hand, to name and display the correctors and the tool-dimensions, retained for the adjustments, on the manufacturing drawings, and, on the other hand, to establish their relationships with the manufacturing dimensions.

The representation of the correctors and the tool-dimensions on the manufacturing drawings

enables us to call them the *pilot dimensions*. A corrector will be represented by a dimension drawn on the surface which it locates (figure 3). This graphical representation makes it possible to indicate that it is not a measurable dimension and that its modification is not absolute but relative to the current location of the surface. A tool-dimension or a program-dimension, is represented as accustomed (C34 on figure 3).

3.1 Determination of the pilot dimensions

The pilot dimensions can be determined manually: Each tool must have a corrector and, if it machines several surfaces, one or more tool or program dimensions to locate them relatively. On the example, the tool (2) machines two surfaces. Let us place, for instance, the corrector of position of tool (2) on surface (3), C3. The dimension C34 locates relatively the surfaces machined by the tool.

These pilot dimensions are the adjustable parameters on the machine used to correct the manufacturing dimensions. On a simple case like the one presented, the influence of the pilot dimensions on the manufacturing dimensions is easy to determine: If the positive direction of the correctors is oriented towards the right of the figure 3, an increase in C2 will increase the manufacturing dimension between the surfaces (1) and (2), CF12, and will decrease dimension CF23 (see figure 3). An increase in C3 will cause an increase in CF23 and CF14. Finally an increase of the tool-dimension C34 will increase CF14. These observations result in the following relationships on the dimension deviations (deviations are noted e):

$$e_{CF12} = e_{C2} \quad (Eq. 1)$$

$$e_{CF23} = -e_{C2} + e_{C3} \quad (Eq. 2)$$

$$e_{CF14} = e_{C3} + e_{C34} \quad (Eq. 3)$$

These relationships can also be obtained systematically by using the technique of the minimal chain of dimensions. To do so, we represent all the dimensions in the form of bi-points: On an axis oriented in the positive direction of the correctors, the surfaces of the part are positioned between themselves, for example by their X-coordinates values (see figure 4). A fictitious surface, representing an invariant surface in position, is added on the left side of the surfaces of the part (surface (0) on figure 4).

All the potential pilot dimensions are thus represented by bi-points connecting the surfaces: Correctors, between the fixed surface (0) and every surface of the part and the tool-dimensions between all the surfaces machined by the same tool (see figure 4).

Starting with the manufacturing dimension having the smallest tolerance, CF23, the minimal path, in terms of number of pilot dimensions, connecting the two surfaces (2) to (3), passes by C2 then C3. In the form of vectorial relation this becomes:

$$\overrightarrow{CF23} = -\overrightarrow{C2} + \overrightarrow{C3} \quad (Eq. 4)$$

or, by projection on the oriented axis:

$$CF23 = -C2 + C3 \quad (Eq. 5)$$

While defining $C = Target_C + e_C$, where C is the value of a dimension, $Target_C$ is its target value and e_C is a deviation compared to its target value, equation 5 becomes:

$$(Target_{CF23} + e_{CF23}) = -(Target_{C2} + e_{C2}) + (Target_{C3} + e_{C3}) \quad (Eq. 6)$$

However equation 5 is checked for the target values:

$$Target_{CF23} = -Target_{C2} + Target_{C3} \quad (Eq. 7)$$

Therefore, there is the following relation on the deviations:

$$e_{CF23} = -e_{C2} + e_{C3} \quad (Eq. 8)$$

Note: We again obtain equation 2 obtained by reasoning.

In the same manner for CF12, we obtain:

$$e_{CF12} = -e_{C1} + e_{C2} \quad (Eq. 9)$$

and for CF14, which has the most important tolerance:

$$e_{CF14} = -e_{C1} + e_{C3} + e_{C34} \quad (Eq. 10)$$

This last manufacturing dimension does not use C4 because the corresponding bi-point was removed when C3 was selected by dimension CF23. Indeed, these two correctors were in competition for positioning tool 2.

Compared to the equations established by reasoning, an additional corrector, C1, appear in the equations. It means that the manufacturing dimensions which depend on it, could also be corrected by modifying the location of the workpiece carrier in the machine. According to machines, this adjustment is sometimes possible (if stop is adjustable). Since there are now more pilot dimensions than manufacturing dimensions, there are several possible solutions to correct the deviations on the manufacturing dimensions (four pilot dimensions for three manufacturing dimensions).

To have a unique solution for the operator, the manufacturing engineer must choose the surface whose position will not be modified. For our example, it is obviously the surface (1) but if its stop had been adjustable, the manufacturing engineer could also have chosen to block surface (2) because of the proximity of the tool (1) with the workpiece carrier, to avoid collisions when modifying the C2 corrector.

The surface (1) being nonadjustable in position, its deviation is definitively null:

$$e_{C1} = 0 \quad (Eq. 11)$$

The relations between the deviations of the pilot dimensions and those of the manufacturing dimensions become (in matrix form):

$$\begin{bmatrix} e_{CF12} \\ e_{CF23} \\ e_{CF14} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} e_{C2} \\ e_{C3} \\ e_{C34} \end{bmatrix} \quad (Eq. 12)$$

3.2 Corrections of the pilot dimensions

The determination of the optimal pilot dimensions for the correction of manufacturing dimensions also makes it possible to obtain their influence on the manufacturing dimensions (equation 12).

By inverting the system of deviation equations it is possible to compute the value of all the corrections that need to be done on the pilot dimensions to compensate the deviations measured on the manufacturing dimensions. The inversion of the system of equations 12 gives:

$$\begin{bmatrix} e_{C2} \\ e_{C3} \\ e_{C34} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} e_{CF12} \\ e_{CF23} \\ e_{CF14} \end{bmatrix} \quad (Eq. 13)$$

3.3 Simulation of the pilot dimensions method

Let us present what could be a real workshop scenario using pilot dimensions.

After having mounted the tools in the machine, the operator machines a first part. Then he measures the deviations on the manufacturing dimensions. Imagine that he obtains the following deviations:

$$\begin{bmatrix} e_{CF12} \\ e_{CF23} \\ e_{CF14} \end{bmatrix} = \begin{bmatrix} -0.2 \\ +0.3 \\ +0.1 \end{bmatrix} \quad (Eq. 14)$$

The matrix equation 13 enables him to deduce the deviations of the pilot dimensions:

$$\begin{bmatrix} e_{C2} \\ e_{C3} \\ e_{C34} \end{bmatrix} = \begin{bmatrix} -0.2 \\ +0.1 \\ 0 \end{bmatrix} \quad (Eq. 15)$$

Correctors C2 and C3 will have to be modified of the quantities opposed to those calculated. The tool-dimension C34 does not require any modification. In the opposite case it would have been necessary to sharpen the tool according to the value of the deviation and to the material possibilities for the operator.

With these modifications, the manufacturing dimensions of the second workpiece will all be on their aimed target. The second workpiece and the following ones will be in conformity until the tool wears are so great that a new modification of the pilot dimensions is needed.

4 Applying the method to an industrial workpiece

This method has been successfully tested in a screw machining company. The part has five finished surfaces (numbered 1 through 5 in the bottom of figure 5) and four roughed surfaces (numbered 2a, 3a, 4a and 5a).

The finished surfaces are located by four design dimensions (indicated above the drawing of the part in figure 5), and the roughed surfaces, by four stock removal dimensions (indicated below the drawing of the part in figure 5).

The part is machined out of a bar by a set of thirteen tools (figure 6). The manufacturing process begins with the translation of the bar until the front surface touches the retractable stop which "realizes" surface 5a. Most of the machining is done with the bar pinched by the chuck of the main spindle. Only the rear chamfers (on the left side of the part in figure 6) are machined on the secondary spindle after the part has been sawed off.

Eight tools machine flat surfaces, either roughed or finished on the part, counting the retractable stop as an adjustable tool (they are colored in gray in figure 6). The others machine either cylinders or cones and do not present any adjustment difficulties.

To adjust this subset of eight tools, we must determine a set of measurable manufacturing dimensions between the different flat surfaces of the part.

Currently, no manufacturing dimension set is established prior to the setting up of the machine. This task is left to the operator who chooses himself a set of dimensions while being in front of the stopped machine. Usually he chooses "Wade dimensions", i.e. dimensions allowing him to adjust independently each tool by the measurement of a single dimension on the part. So, on this part, the operator would measure the dimensions between each machined surface and surface 1, performed by the sawing off of the part needed to be able to remove it from the machine for measuring (this is the most common method used in the screw machining industry).

Even though he could group several machining operation before sawing off the part, he often adjusts individually each tool and saws off a new workpiece for each one of them. He could not do so with "Bourdet manufacturing dimensions". Thus, after adjusting the sawing tool by performing a first sawing operation, he manufactures an unfinished part, thus rejected, for each of the seven other tools machining flat surfaces. In the same way, he adjusts the tools performing cylinders or

cones. In total, for this workpiece, counting reasoning or calculation errors, the operator scraps up to fifteen setup workpieces for the initial setting up of this machine.

In addition to material consumption, this method leads to long setup times and therefore to productivity losses. In addition, the manufacturing dimensions that he measures being very different from the design dimensions, he also measures the latter to ensure himself of the conformity of the workpieces. Tolerances on these manufacturing dimensions could help avoid measuring the design dimensions, but on the other hand they could lead to scrap conform workpieces in regard to the design dimension tolerances, and this, amplified by the fact that these tolerances are much smaller than the design dimension tolerances. Thus, even in seeking to maximize the tolerances of the manufacturing dimensions between the finished surfaces, which are the ones that would enable one to decide of the conformity of the workpiece, many of these tolerances would be two times smaller than the smallest tolerances of the design dimensions (see table 1). This can be explained by the fact that most design dimensions would be measured indirectly by two manufacturing dimensions.

By keeping surface 1 as the reference surface, the "Bourdet method" leads, on this example, to a set of twelve manufacturing dimensions: The eight "Wade dimensions" plus the four dimensions corresponding directly to the design dimensions. This system having too many manufacturing dimensions, we can eliminate the four last "Wade dimensions" (see table 1) and conserve instead the manufacturing dimensions that correspond directly to the design dimensions (see figure 7).

By favoring the tolerances of the manufacturing dimensions that correspond directly to the design dimensions, we can affect each one of them with the entire tolerance of its corresponding design dimension (see table 2).

Thus the measurement of these four manufacturing dimensions (below the drawing represented in figure 7) allows, on the one hand, the calculation of the corrections needed to be done for each tools and, on the other hand, the conformity check of the workpiece towards its design dimension tolerances.

In addition, the measuring of each manufacturing dimension requires the completion of two finished surfaces which necessarily leads to the grouping of machining operations before the sawing off of the part for measuring. In fact, it is even possible, for this industrial example, to measure all the manufacturing dimensions by only realizing two set up workpieces: The first workpiece for the measuring of the manufacturing dimensions positioning the roughed surfaces (above the drawing in figure 7) and a second one for the measuring of the manufacturing dimensions corresponding to the design dimensions positioning the finished surfaces. The operator has thus been able to measure the deviations of the height manufacturing dimensions in only two workpieces instead of seven previously (see table 3).

The operator notices that the last workpiece is not conform. Only manufacturing dimension CF3-4 meets its tolerance.

By choosing to place the corrector on surface 4 for the finishing tool manufacturing surfaces 3 and 4, we established the relationship matrix between the manufacturing dimension deviations and those of the pilot dimensions using the method described in Section 3 (see equation 16).

$$\begin{bmatrix} e_{C2a} \\ e_{C3a} \\ e_{C4a} \\ e_{C5a} \\ e_{C2} \\ e_{C34} \\ e_{C4} \\ e_{C5} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e_{CF1-2a} \\ e_{CF1-3a} \\ e_{CF1-4a} \\ e_{CF1-5a} \\ e_{CF1-4} \\ e_{CF2-4} \\ e_{CF3-4} \\ e_{CF4-5} \end{bmatrix} \quad (Eq. 16)$$

This matrix equation, programmed into a spreadsheet, enables us to compute the corrections that need to be done for each pilot dimension (see table 4).

By correcting the tools with the determined values, except for the tool dimension C34 that would have needed sharpening of the shape tool, deviations on manufacturing dimensions have been cancelled (except for CF3-4 and in the manufacturing and measuring scattering near) and the third workpiece has been conform regarding the design dimensions.

5 Conclusion

The pilot dimensions method consists in using manufacturing dimensions having the nearest relationship to the design dimensions of the product in order to reduce as much as possible tolerance loss during the transfer of tolerances of one system to the other. The manufacturing dimension tolerances can then be used to judge the conformity of the workpieces as the operators are today accustomed to do it. The pilot dimensions, which correspond to the correctors and to the tool or program dimensions, are represented on the manufacturing drawings and calculation sheets are provided to the operator, either in paper form or as a spreadsheet. This enables him to calculate the corrections that need to be done on the pilot dimensions according to the deviations noted on the manufacturing dimensions of the last produced part. This method removes the current mistakes of operators related to the fact that one asks them to mentally carry out the link between the correctors and the manufacturing dimensions in front of the machines. By using this method, a great amount of time is saved and the number of rejected workpieces is largely diminished.

Currently we are carrying out a reflection on the limits that are to be set on the manufacturing dimensions and the pilot dimensions and under which the adjustments will not have to be made. This production steering, by using limits, is already well-known by the operators in companies using the techniques of Statistical Process Control.

By using manufacturing dimensions close to the design dimensions as the pilot dimensions method allows it, the steering and the conformity verification of the products can be carried out with the same set of dimensions.

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Table 1. Best tolerances for the "Wade manufacturing dimensions set".

	Tolerance
CF1-2a	0.34
CF1-3a	0.36
CF1-4a	0.36
CF1-5a	0.46
CF1-2	0.06
CF1-3	0.04
CF1-4	0.04
CF1-5	0.14

Table 2. Best tolerances for the "Bourdet manufacturing dimensions set".

	Tolerance
CF1-2a	0.12
CF1-3a	0.14
CF1-4a	0.22
CF1-5a	0.24
CF1-4	0.18
CF2-4	0.10
CF3-4	0.08
CF4-5	0.18

Table 3. Tolerances and deviations of the manufacturing dimensions, measured on two set up workpieces.

	Measured value	Tolerance
e_{CF1-2a}	-0.12	± 0.06
e_{CF1-3a}	0.17	± 0.07
e_{CF1-4a}	-0.07	± 0.11
e_{CF1-5a}	-0.20	± 0.12
e_{CF1-4}	0.15	± 0.09
e_{CF2-4}	-0.08	± 0.05
e_{CF3-4}	-0.02	± 0.04
e_{CF4-5}	0.12	± 0.09

Table 4. Determined corrections for the pilot dimensions.

	Correction
C2a	0.12
C3a	-0.17
C4a	0.07
C5a	0.20
C2a	-0.23
C3a	0.02
C4	-0.15
C5	-0.27

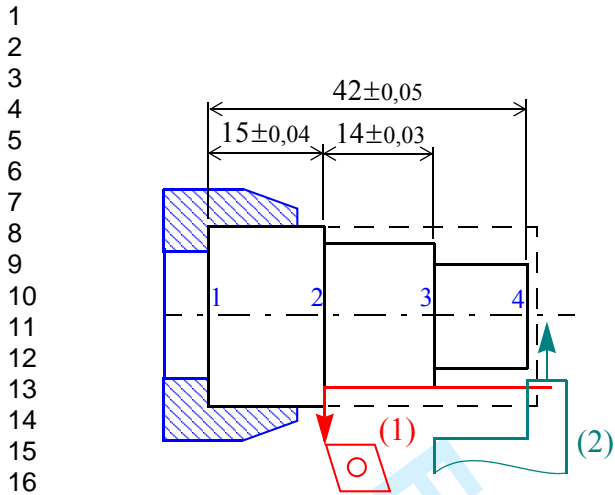


Figure 1. Process of obtaining a part with, on the top, the design dimensions of the part.

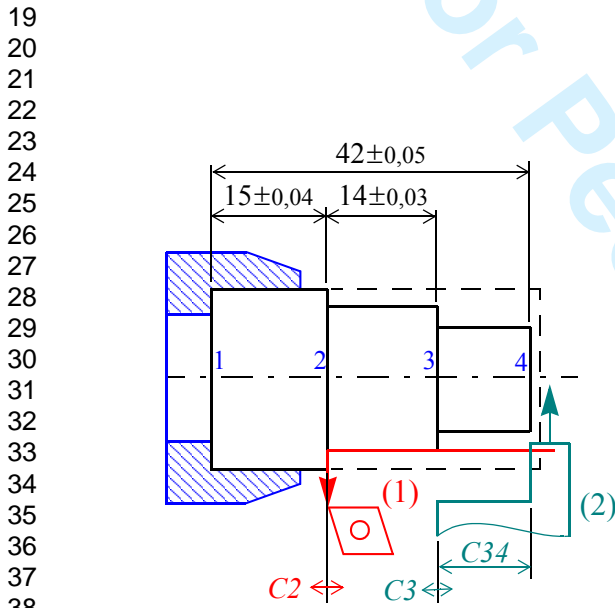


Figure 2. Manufacturing dimension with Bourdet's method.

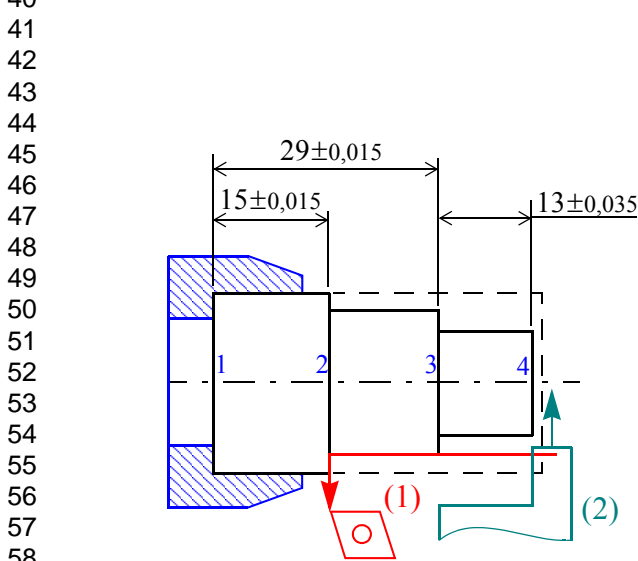


Figure 3. Manufacturing dimensions with Wade's method.

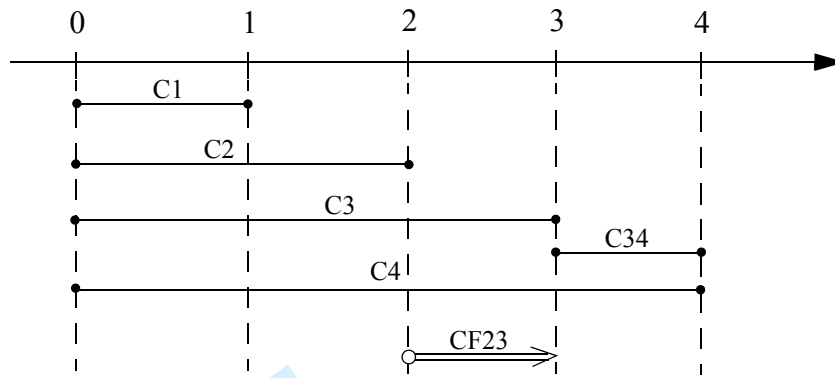


Figure 4. Graphical representation of all the potential pilot dimensions and of one of the three manufacturing dimensions.

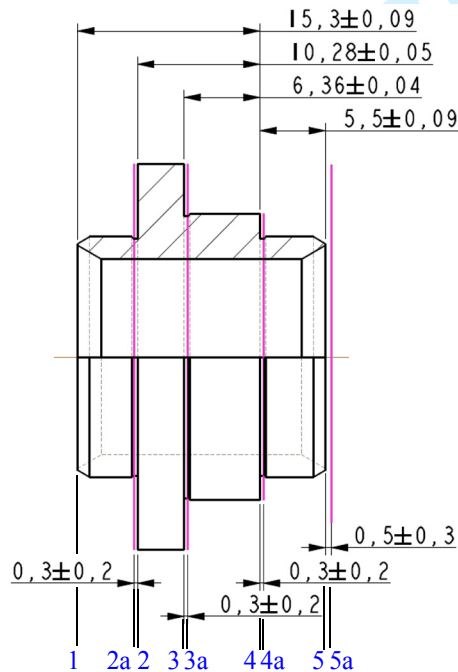


Figure 5. The industrial part with four design dimensions and four stock removal dimensions.

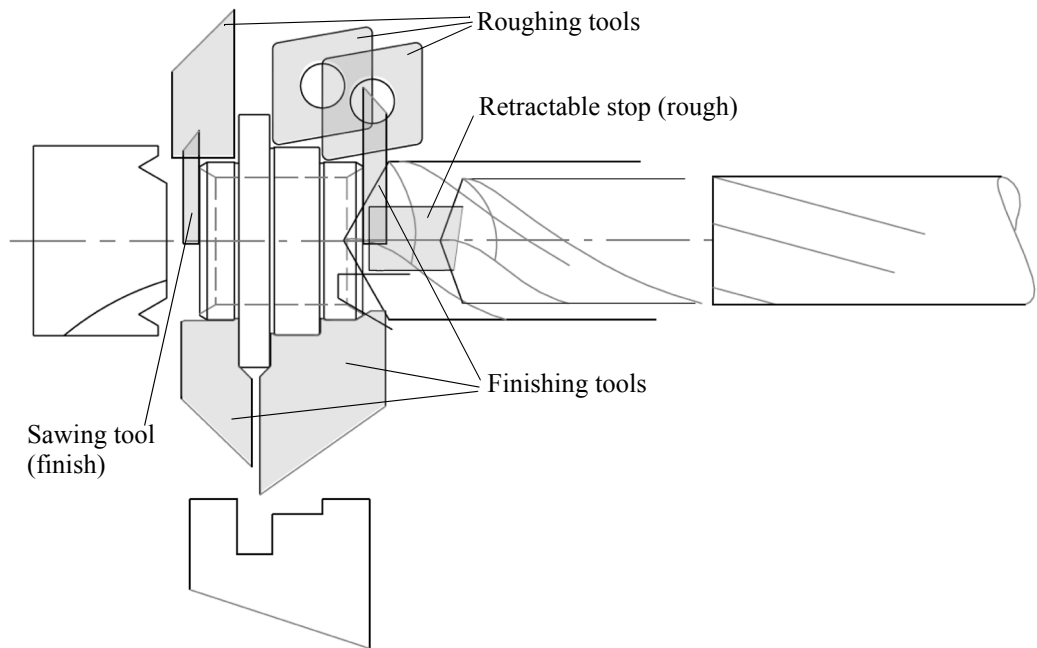


Figure 6. The thirteen tools used for manufacturing the part.

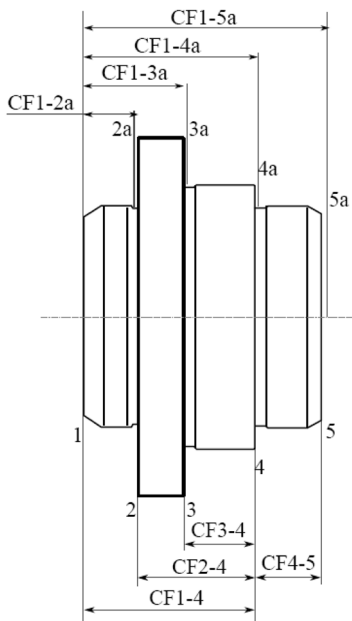


Figure 7. Manufacturing dimension set established for the industrial part.